SOAR 2011: Attitude Control Augmentation Using Wing Load Sensing – A Biologically Motivated Strategy

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

CONTROL SYSTEM COMPARISON
Man-Made vs Natural Systems

NATURAL SYSTEMS

SENSING

Complex Integration of: Pressure, Force, Rate, Thermal, Chemical and Optical Sensors.
Pervasive Nervous System for Interconnecting Control to Numerous Sensing Modalities

CONTROL

Straightforward.
Feedback Activated Response
Non-Linear Thresholding
Pattern Generation

CHARACTERISTICS:

+Robust to a wide range of operational variability.
+Wide tolerance to individual variations.
+Tolerance to damage.

- Unpredictable (non-linear) behavior.
-Sometimes high individual mission failure rate.
(398 out of 400 salmon fail)

Evolutionary Objective: Population fills an ecological niche. Numerous competing pressures.

MAN-MADE SYSTEMS

SENSING

Straightforward. Few Sensors. Highly Localized. Typically Optimized for Limited Purpose.

CONTROL

Complex modeling and estimation: Adaptive parameter estimation, gain scheduling, data dependent, model based, Lyapunov stability theory, Modern control theory, etc.

CHARACTERISTICS:

+Highly tuned predictable behavior.
+High individual success (Pk).
+Software sophistication not hardware.

- Data dependence (Wind Tunnel data, etc.)
- Brittle designs – limited operational range.
-Expensive to develop and field.

Design Objective: Individual success.

Problem Statement

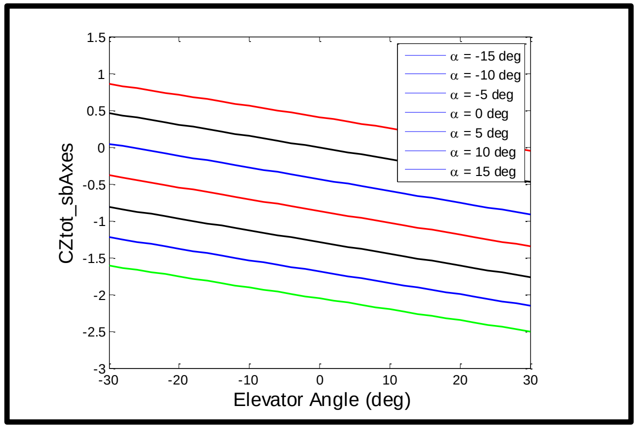
-For autonomous systems to perform their missions, robust, fault tolerant flight control systems will be required, along with a high level of disturbance rejection for stabilized optical sensing.

- Can high latency optical feedback augmented by low-latency wing strain sensors explain observations in natural systems?

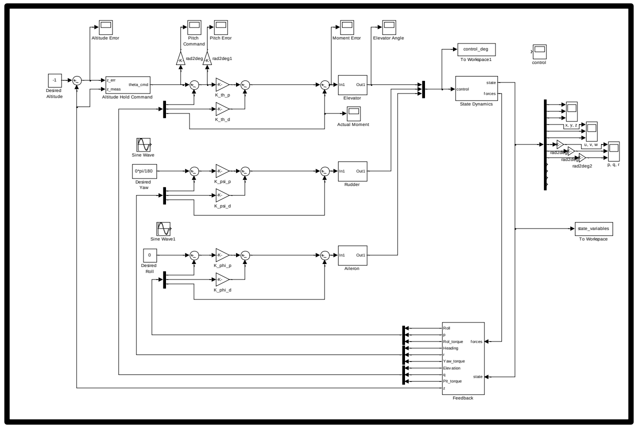
-Can strain sensors on the wings increase stability and robustness while eliminating the need for a dedicated rate gyro (Coriolis sensor)?

Simulation Approach

AFRL GenMAV



Aero Characteristics Using AVL

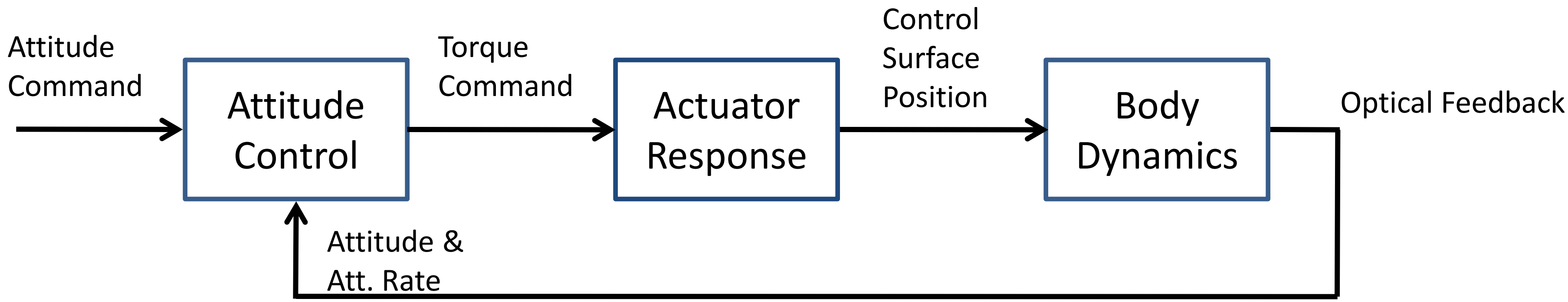


6DOF Simulation and Control Constructs Implemented in Simulink

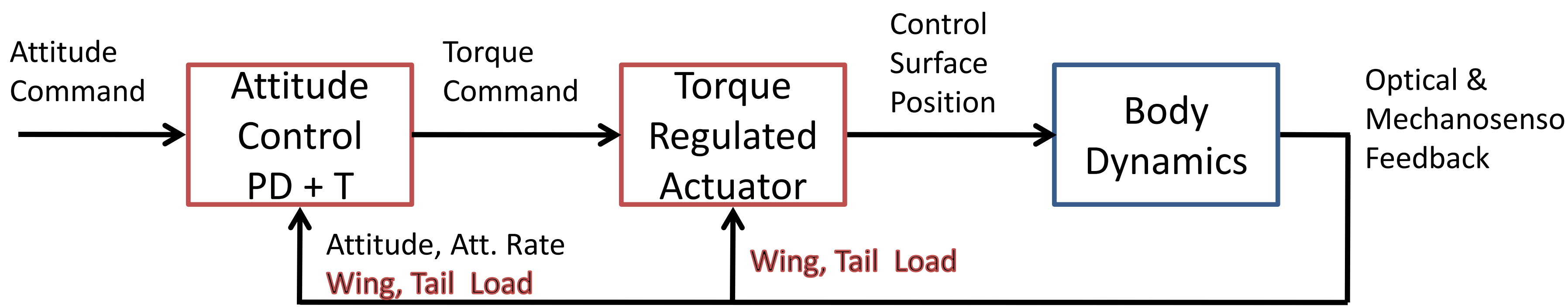
- Configuration with Aileron and Rudder
- Body Torques Around CG Assumed Observable Through Mechanosensing
- Simple PD Attitude Control, PID Altitude
- Dryden Turbulence Model with 2 m/s Equivalent Wind Speed

Force Feedback Augmentation of Attitude Control

Baseline Attitude Control



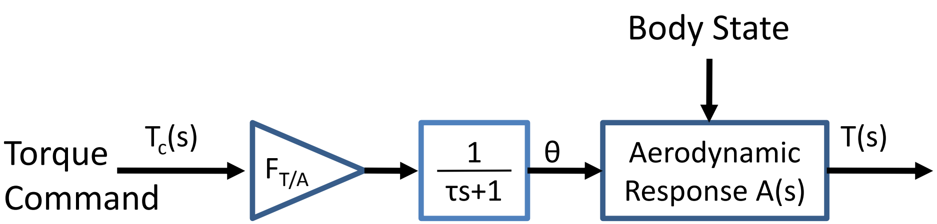
Body Torque Augmented Control

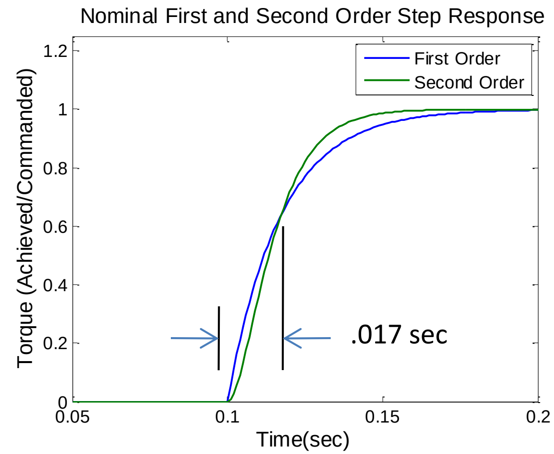


Direct measure of torque on the body potentially provides a low latency signal to control actuator position and optimize attitude control performance.

Baseline and Closed-Loop Actuator Models

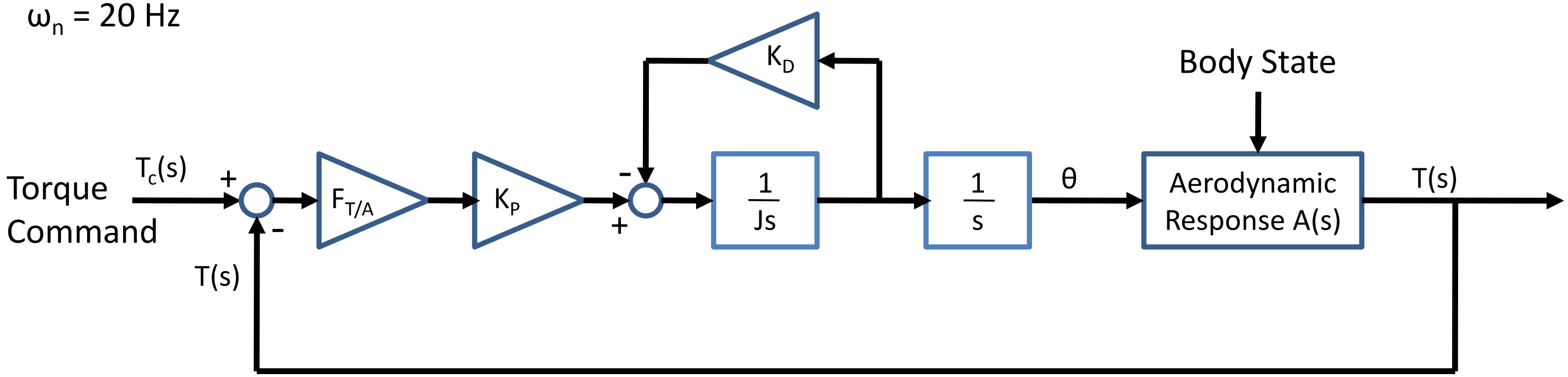
Baseline – First Order Actuator





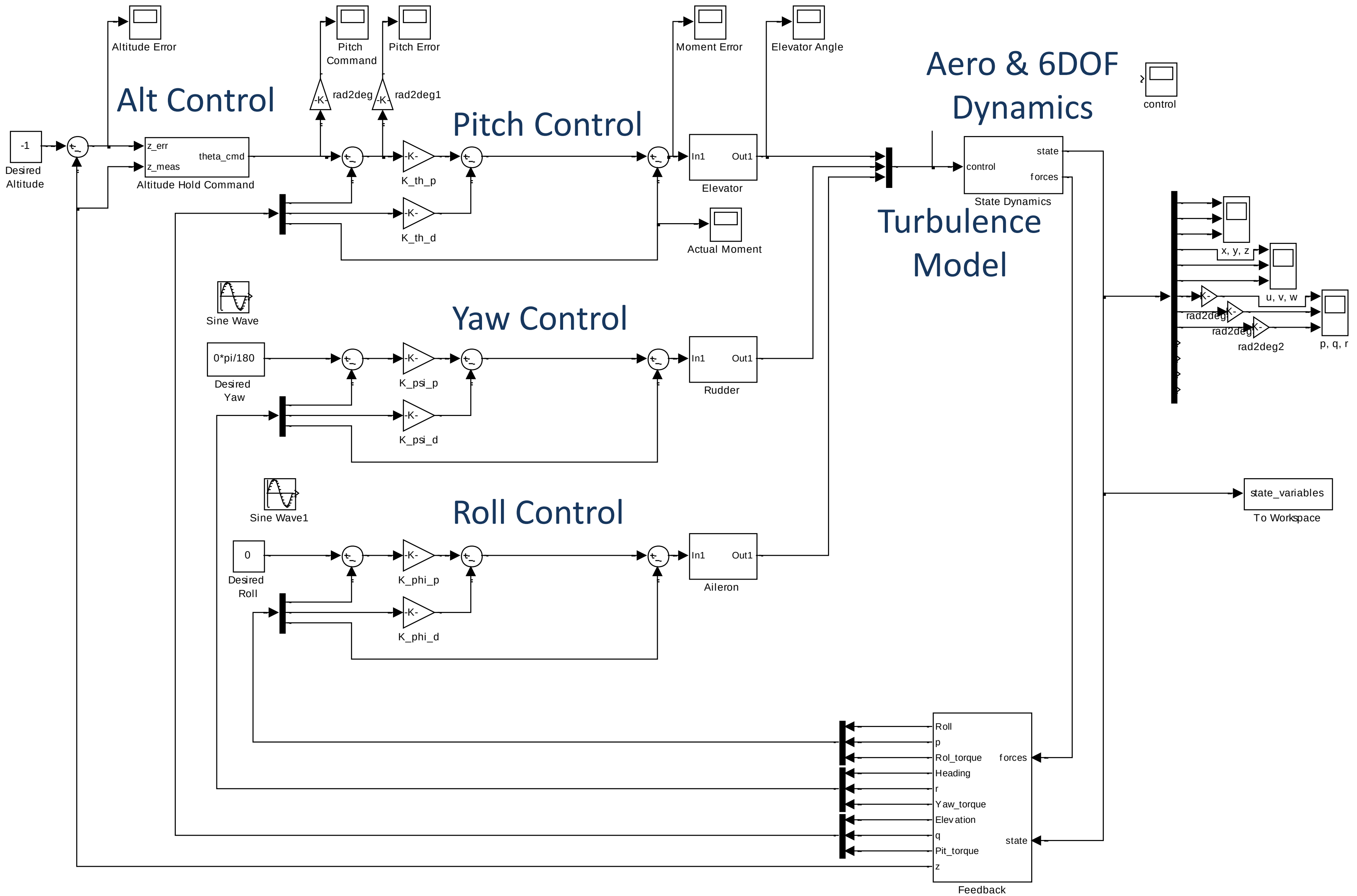
Body Torque Regulated Actuator Model

ω_n = 20 Hz



- Error in achieved body torque drives actuator position as opposed to knowledge of aerodynamic characteristics.
- Time constants for both actuators were nominally tuned to .017 seconds.

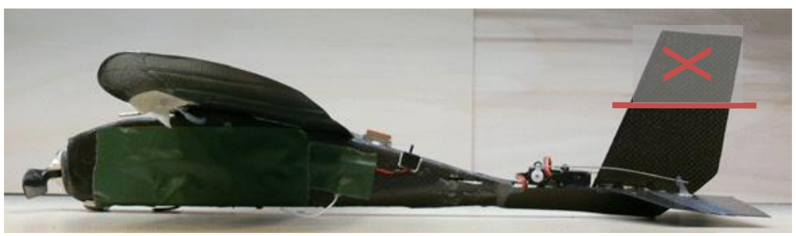
6DOF Simulation Structure



Test Case Description

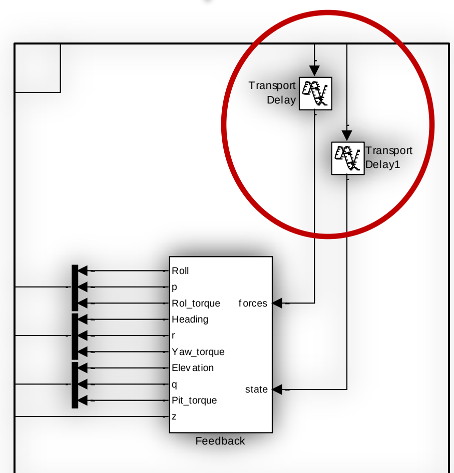
CASE 1 – Control Force Degradation With and Without Torque Feedback. 2 m/s turbulent wind field.

$$\vec{T}_{achieved} = \vec{T}\left(\frac{\delta_{elev}}{2}, \frac{\delta_{rud}}{2}, \frac{\delta_{ail}}{2}\right)$$



CASE 2 - Impact of Optical Feedback Latency With and Without Torque Feedback. 2 m/s turbulent wind field.

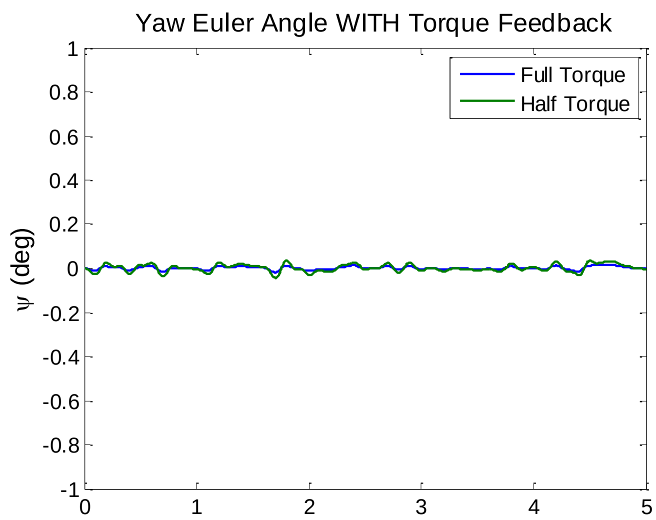
Sensor	Delay
Torque	3 ms
Optical Rate & Position	10, 30, 50 ms

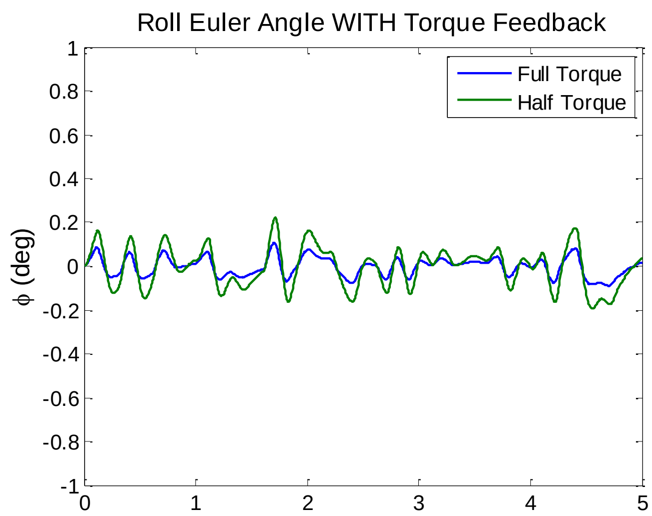


Degraded Control Capability

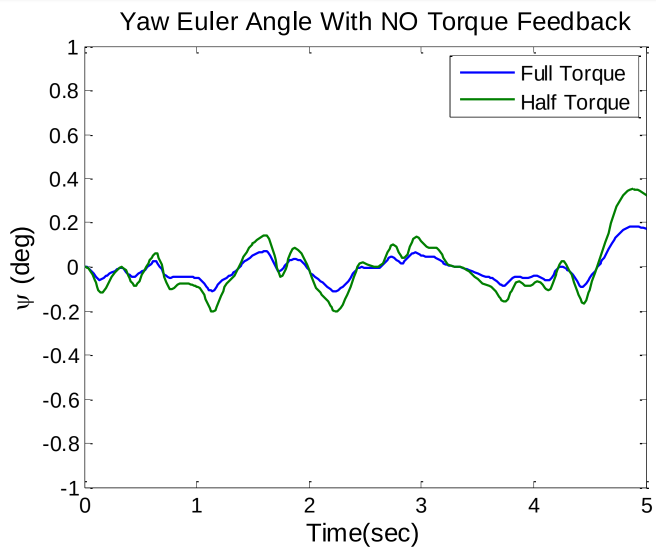
Yaw & Roll Response

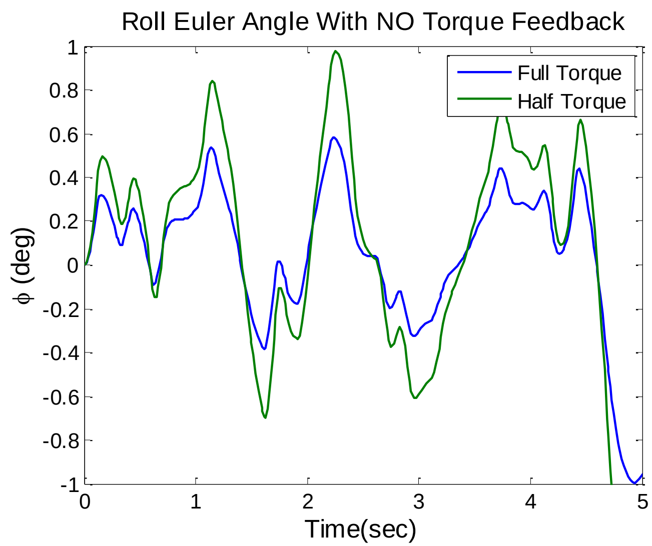
WITH Torque Feedback →





WITHOUT Torque Feedback →

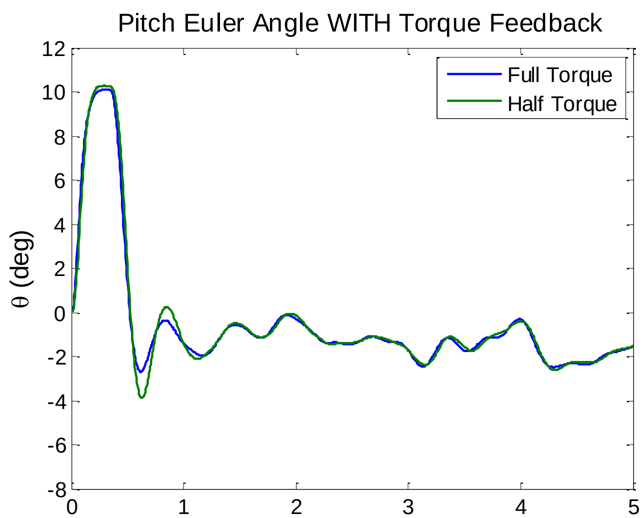


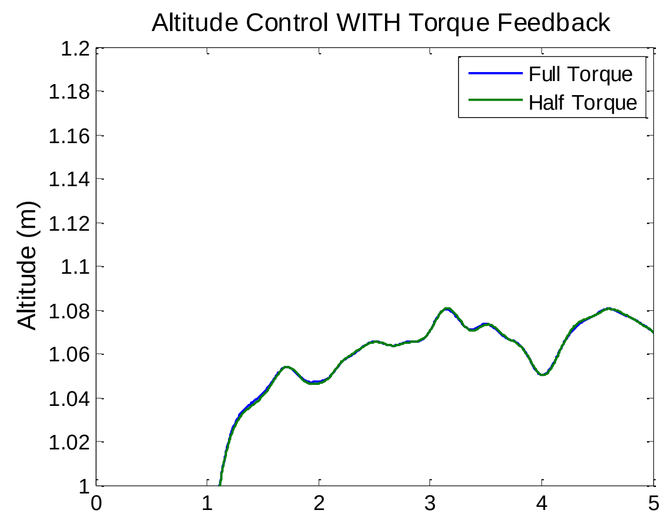


Degraded Control Capability

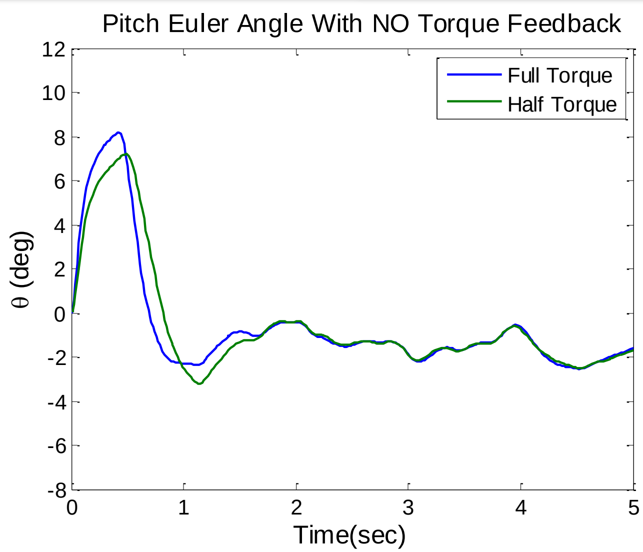
Pitch & Altitude Response

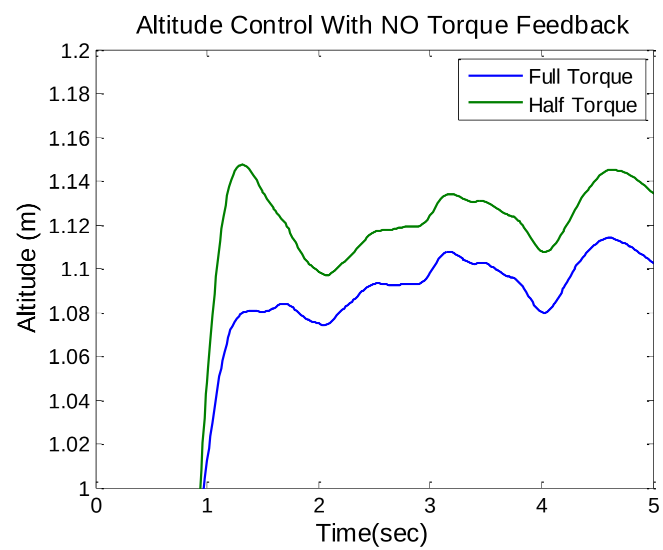
WITH
Torque
Feedback





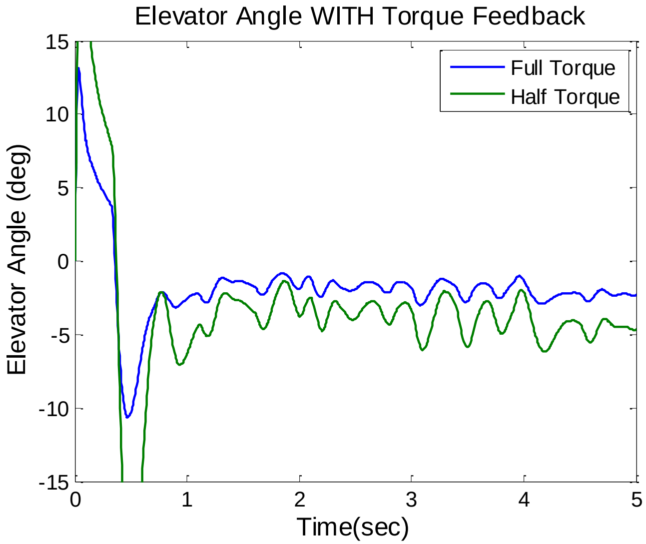
WITHOUT
Torque
Feedback

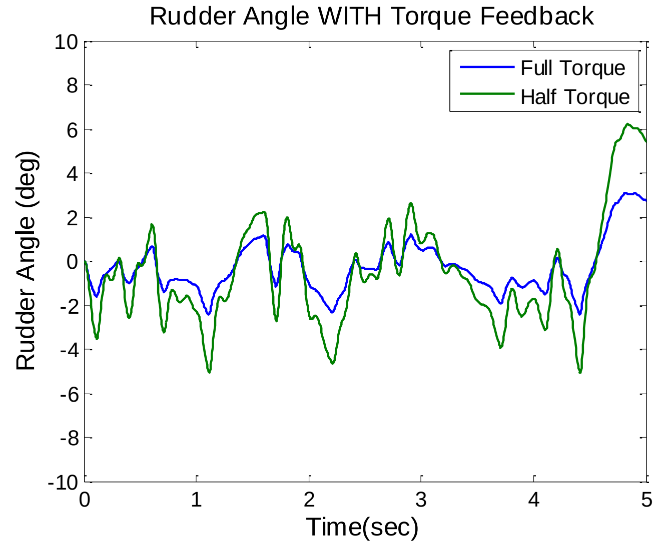


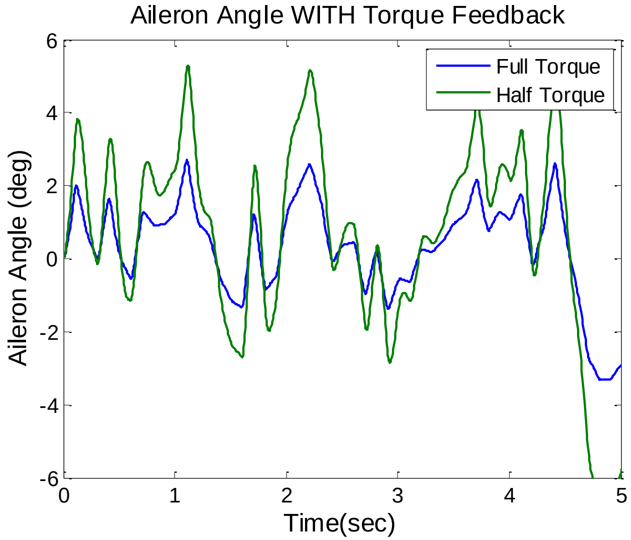


Control Surface Response

Full and Degraded Control Comparison







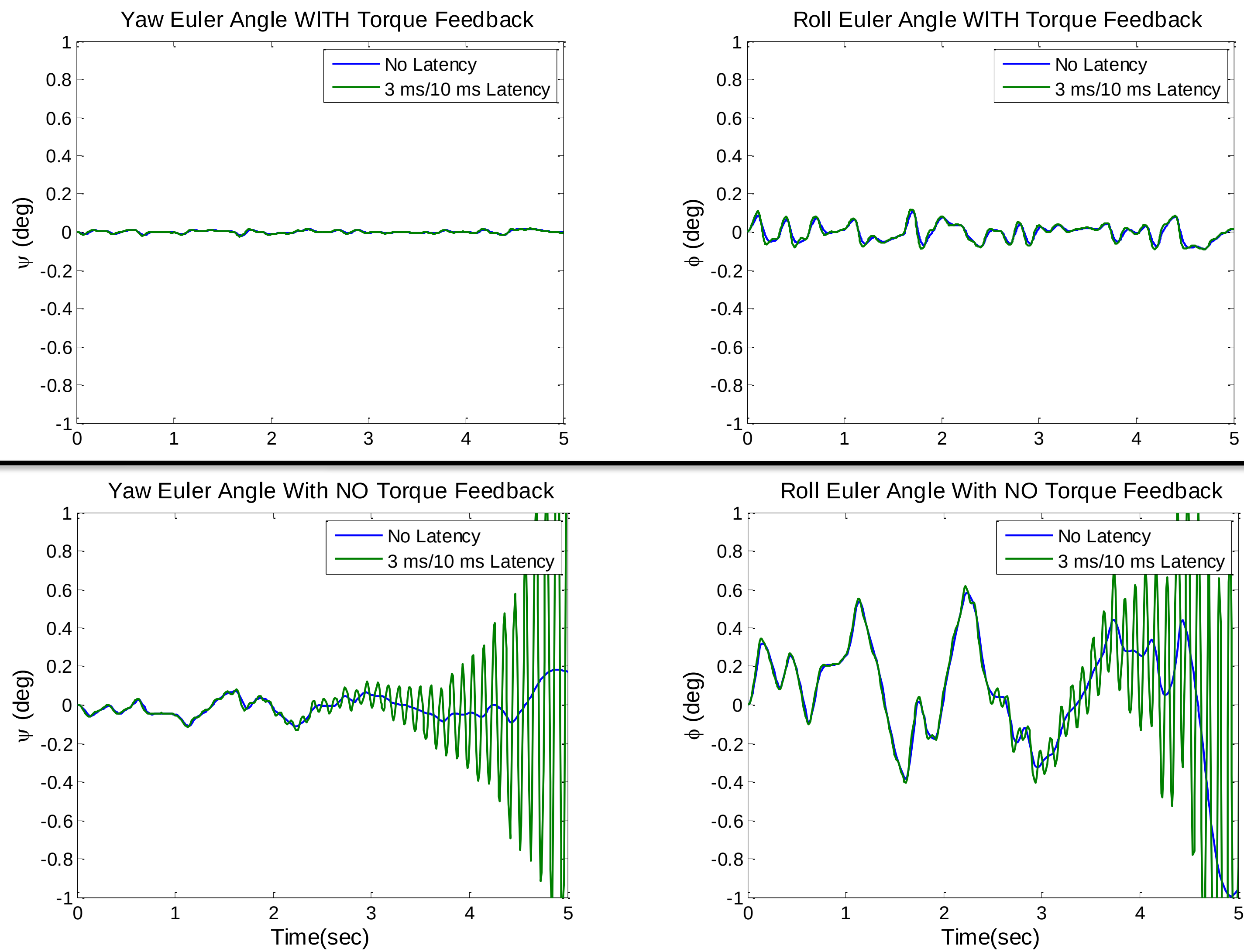
The response of the control surfaces in the presence of compromised torque generation is significantly higher to compensate for the degradation.

Added Latency

(3 ms Torque | 10 ms Optical)

WITH Torque Feedback

WITHOUT Torque Feedback



Optical Latency Compensation

Baseline Control Gain Definition

$$\begin{aligned} Commanded\ Torque &= J\ddot{\theta} \\ &= -J\omega_n^2(\theta_{meas} - \theta_{com}) - J2\zeta\omega_n\dot{\theta}_{meas} \\ &= -K_p(\theta_{meas} - \theta_{com}) - K_d\dot{\theta}_{meas}, \end{aligned}$$

Taylor Series Compensation For Optical Latency

$$\dot{\theta}_{est} = \dot{\theta}_m + \frac{T_m}{J}\Delta t_{opt}$$

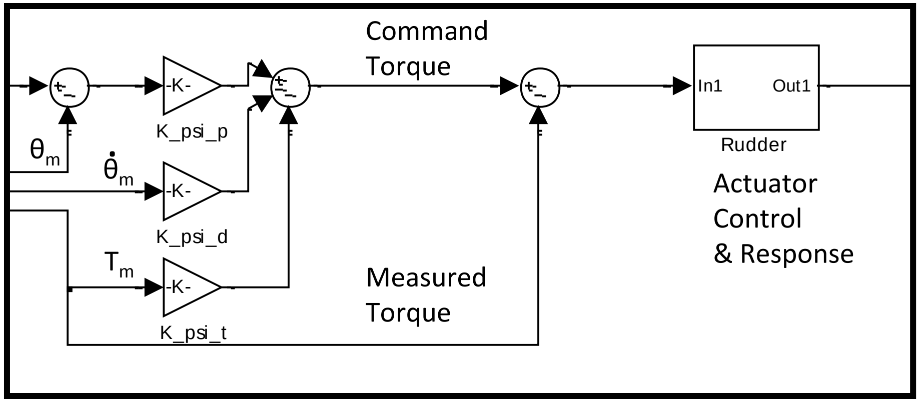
$$\begin{aligned} \theta_{est} &= \theta_m + (\dot{\theta}_m + \frac{T_m}{J}\Delta t_{opt})\Delta t_{opt} + \frac{T_m}{2J}\Delta t_{opt}^2 \\ &= \theta_m + \dot{\theta}_m\Delta t_{opt} + \frac{3T_m}{2J}\Delta t_{opt}^2. \end{aligned}$$

Control With Body Torque Augmentation

$$Commanded\ Torque = -\bar{K}_p(\theta_m - \theta_{com}) - \bar{K}_d\dot{\theta}_m, -\bar{K}_t T_m.$$

Final Form of Gains

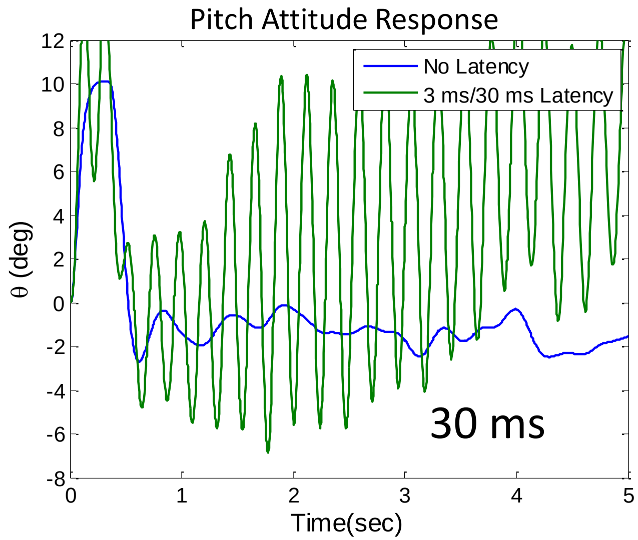
$$\begin{aligned} \bar{K}_p &= K_p \\ \bar{K}_d &= (K_p\Delta t_{opt} + K_d) \\ \bar{K}_t &= \left(K_p\frac{3\Delta t_{opt}^2}{2J} + K_d\frac{\Delta t_{opt}}{J}\right) \end{aligned}$$



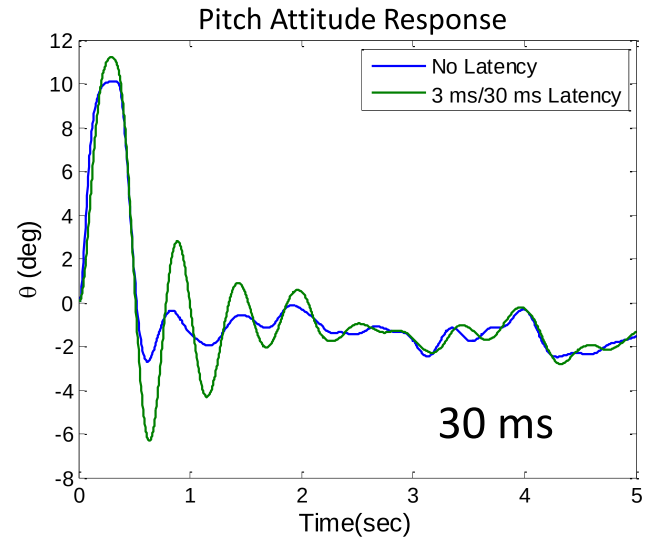
Latency Compensation Results

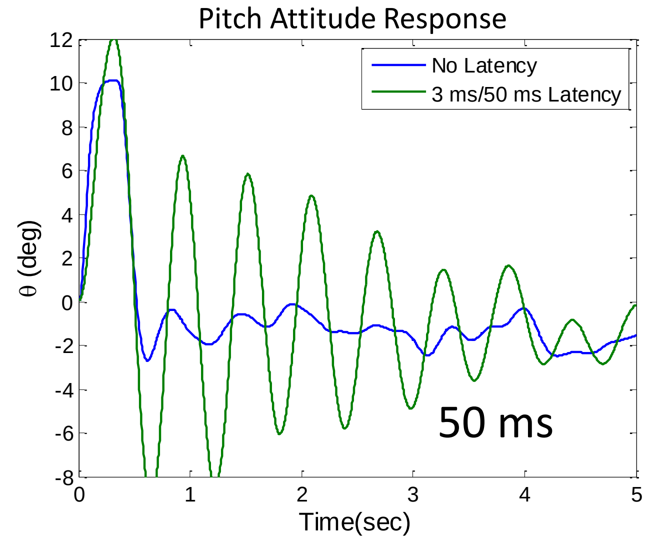
Torque Actuator Regulation – All Cases

PD Attitude Control Only



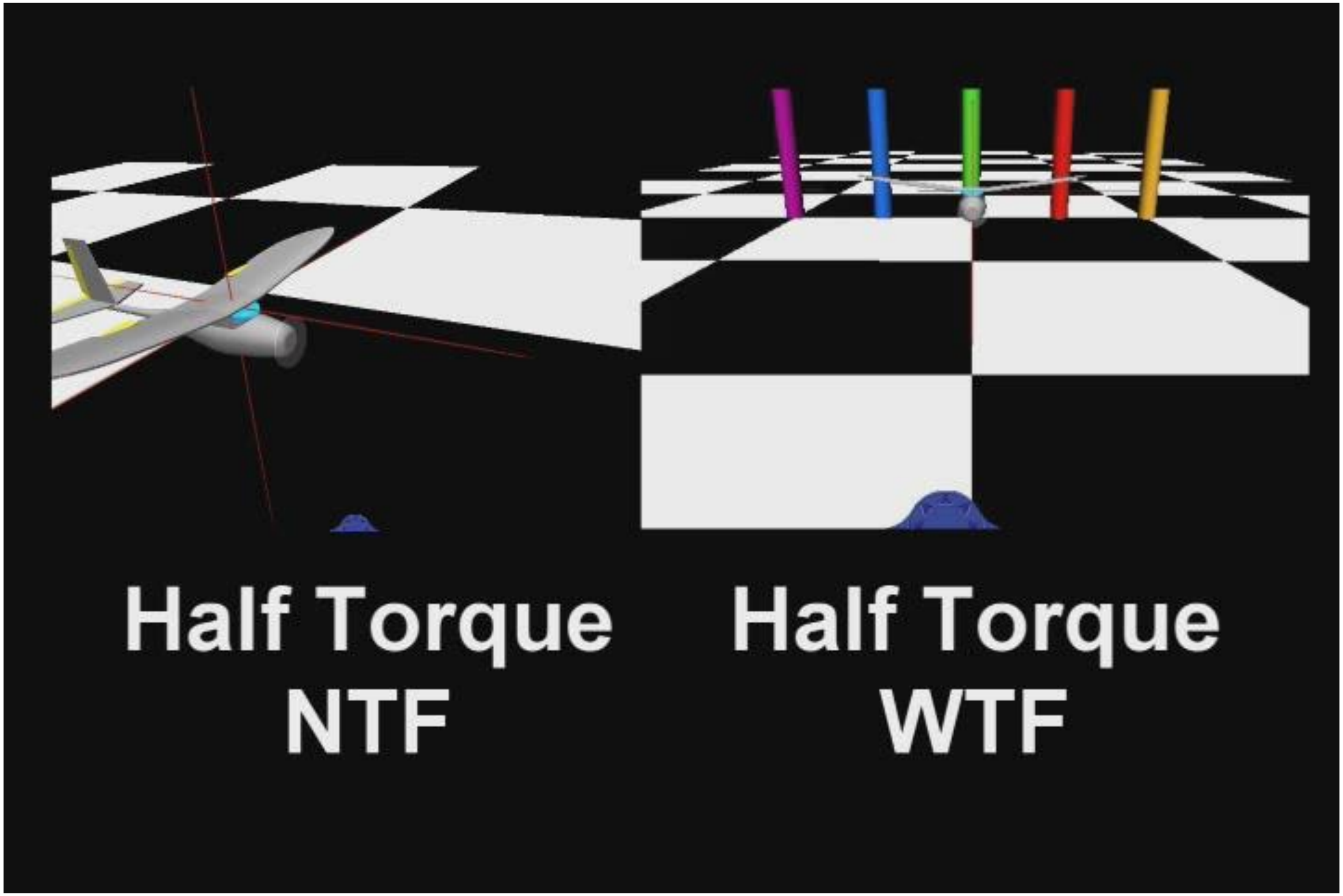
PD-T Attitude Control





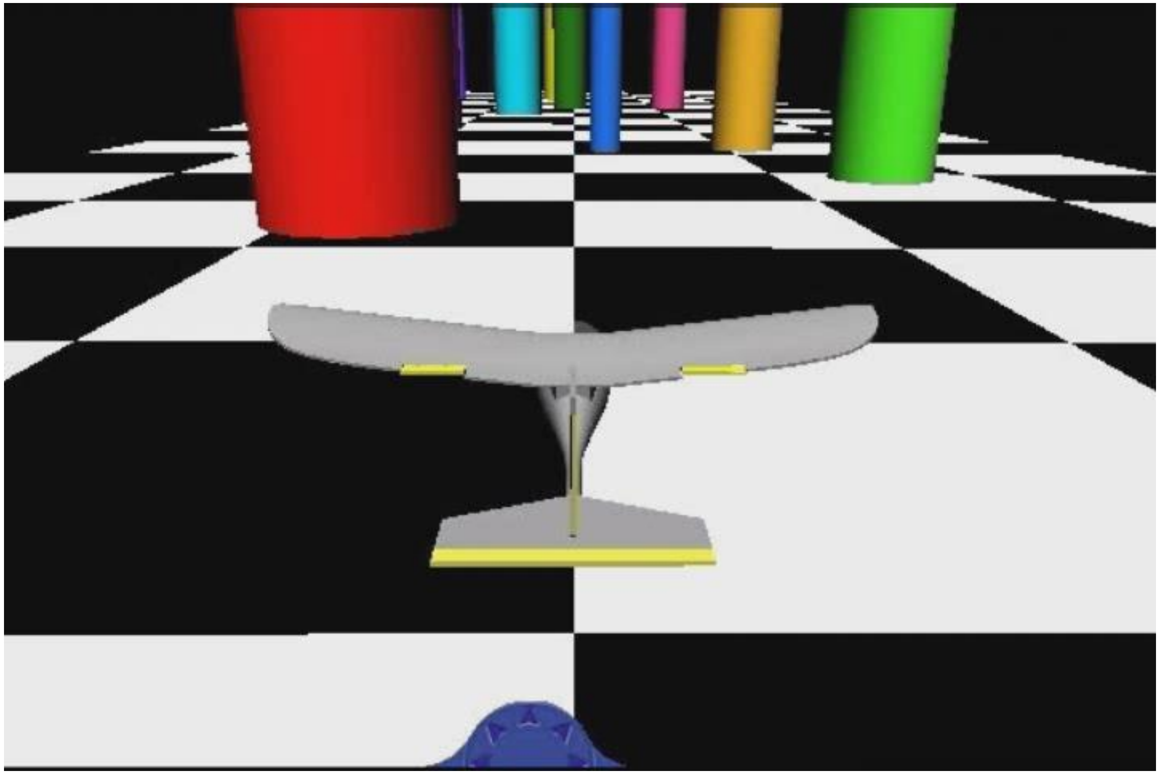
- Addition of torque feedback to the attitude control law provides significant benefit to response.
- Excitation of the actuator loop had to be reduced by increasing actuator damping.
- The latency in conjunction with the initial altitude step function still excited a damped oscillation in the outer altitude hold loop.

Video Animation



- Euler Angles Magnified By 4x
- Turbulence Induced Disturbances
- 50% Control Effectiveness

Vision Based Obstruction Avoidance Agility Demonstration



- Growth Rate Activated Obstruction Avoidance
- Body Torque Feedback to Actuators
- Autonomous Flight Control

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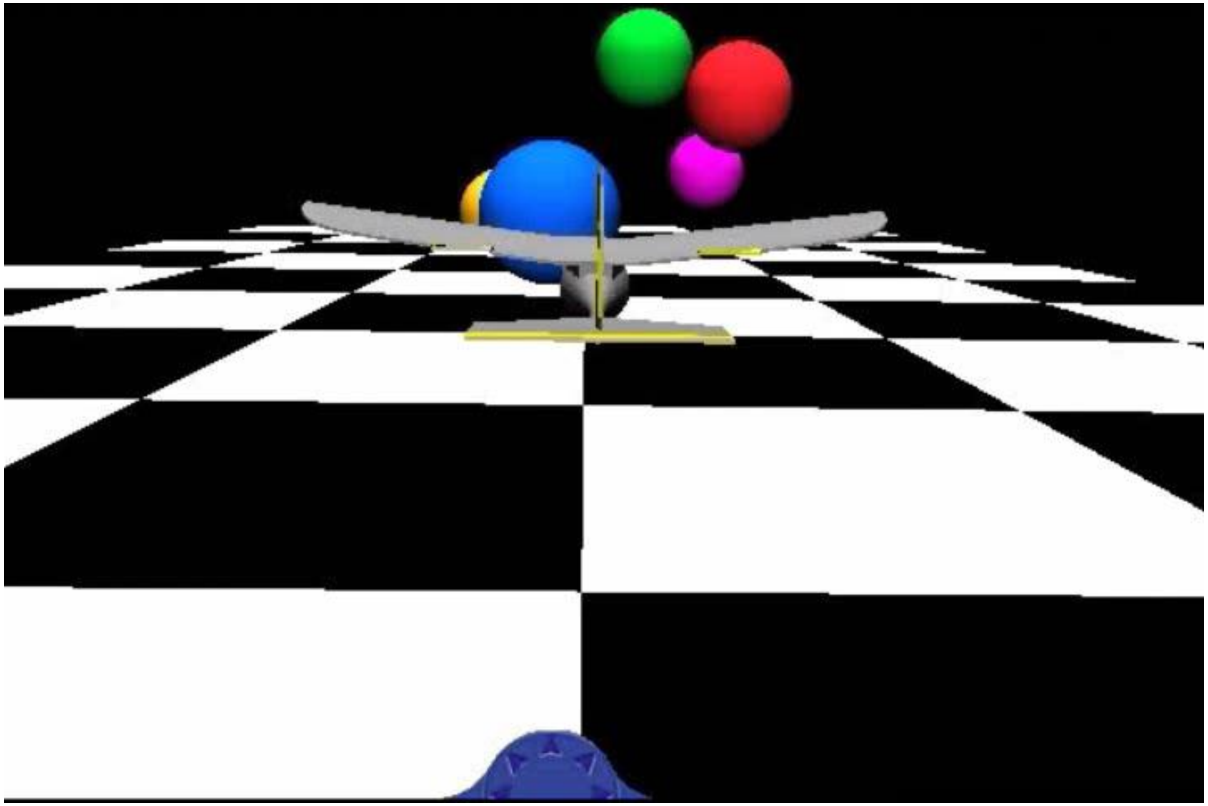

Conclusions

- Body torque feedback has the potential to improve performance and robustness of MAV attitude stability.

  - **Turbulent disturbance rejection is markedly improved using body torque error to control actuator position.**

  - **Uncertainty in control capability and aerodynamic characteristics can be robustly dealt with using a torque feedback approach.**

  - Torque feedback can be used to compensate for high levels of optical latency.

- The requirement for a dedicated angular rate sensor can potentially be eliminated if not required for navigation purposes.

- Additional work is required to design and demonstrate specific strain sensing implementations to measure signals proportional to torque.

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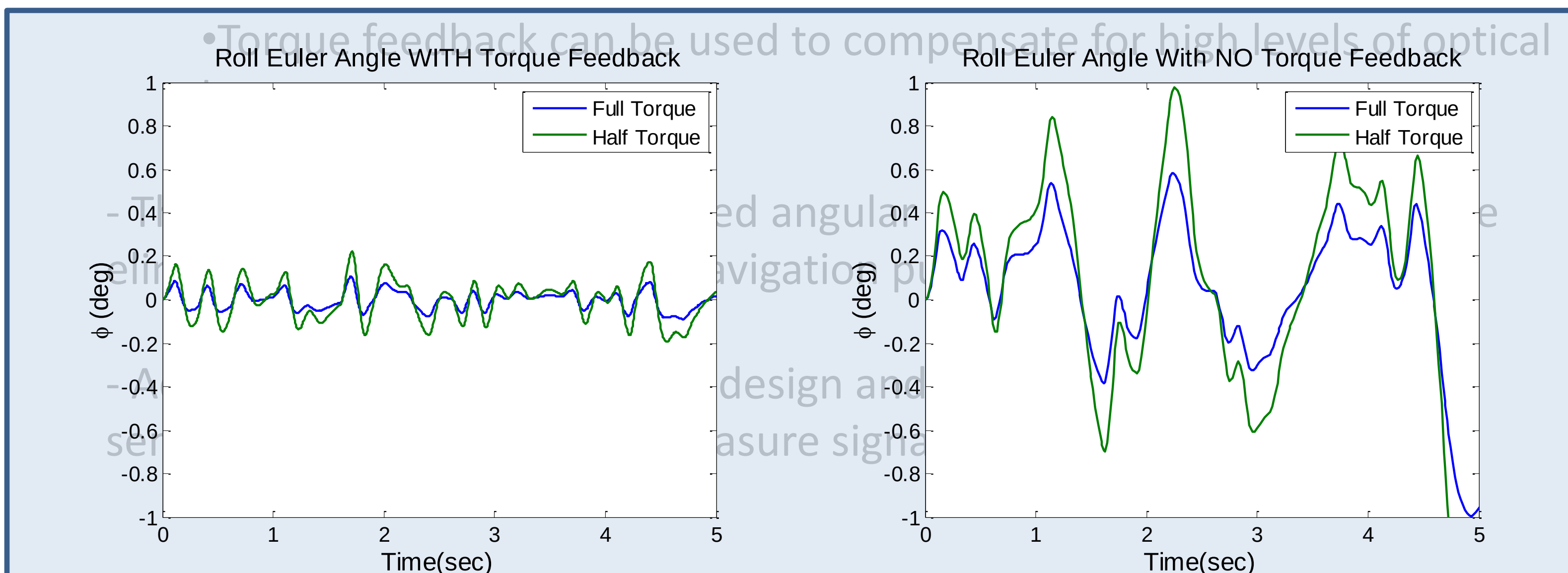

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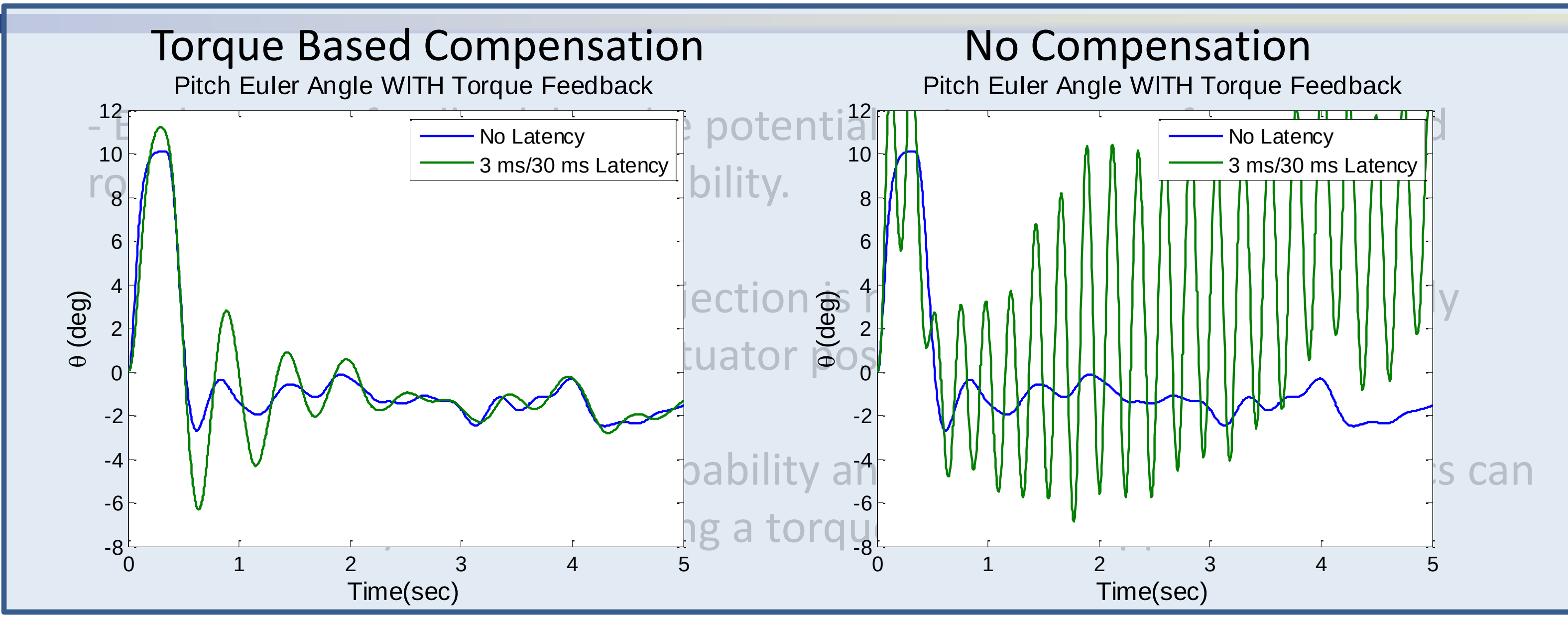

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